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Demand Response From the Control of Aggregated Inverter Air Conditioners

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ABSTRACT Inverter air conditioners (ACs) account for a large proportion of air conditioning loads in many countries and, thus, contribute significantly to the peak loads in these areas, especially in summer. On the other hand, as an important category of thermostatically controlled load with thermal energy storage capability, inverter ACs also have the potential to provide considerable flexibility for electric power systems that are faced with increasing challenges posed by high penetration of renewable power generation. This paper focuses on the demand response from the control of the aggregated inverter ACs for load reduction. A virtual energy storage system (VESS) model that encapsulates the room with an inverter AC was established based on the electric model of an inverter AC and the thermodynamic model of a room. Based on the VESS model, a virtual state of charge (VSOC) priority-based load reduction control method with temperature holding and linear recovery strategies was proposed. The VSOC priority based control was designed to decrease the negative impact of load reduction on customers' thermal comfort from the perspective of the whole AC population. The temperature holding strategy was designed to reduce the electric power of an AC while ensuring that the indoor temperature is always below the allowable limit. The linear recover strategy was proposed to reduce the load rebound after load reduction. Four cases were studied regarding the operation and load reduction of the 100 inverter ACs, and the simulation results verified the models established and the effectiveness and advantages of the proposed load reduction control method.

INDEX TERMS Inverter air conditioner, demand response, load reduction, virtual energy storage system.

I. INTRODUCTION

With the global consensus on preventing global warming and boosting sustainable development, there is a rapidly increasing penetration of renewable power generation in electric power systems. The intermittency and randomness of renewable energy, such as wind and solar energy, make it even more difficult and costly for power systems to maintain the balance between supply and demand. Furthermore, the associated decreasing share of conventional generators, such as thermal and hydro generating units, reduces the flexibility at the supply side of power systems, making the situation even more critical.

Against this background, to utilize the flexibility at the demand side of power systems becomes increasingly important, and there have been a huge number of research activities and industrial practices on demand response across the world [1]. Within the wide range of flexible loads, thermostatically controlled loads (TCLs) are important flexible resources due to their large electric power consumption and thermal energy storage capability. Within certain ranges, the power consumption of TCLs can be shifted, reduced or reshaped without compromising customers' thermal comfort. Therefore, there have been abundant studies made on utilizing TCLs to provide multiple types of demand response services, including load following [2], frequency response [3], operating reserves [4], renewable generation following [5], voltage stability improvement [6], etc.

Air conditioning loads are one of the major components of TCLs, which account for a large proportion of total and peak loads in many areas especially in summer, such as the south of China, California in the U.S., etc. As a result,

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extensive studies have been conducted regarding the demand response from both residential (such as those in [7]–[9]) and commercial (as reviewed in [10]) air conditioning loads.

Most existing studies regarding the demand response from air conditioners (ACs) focus on single speed ACs. However, in recent years, the number of inverter ACs keeps growing, accounting for a significant share of total ACs installed in many areas and countries. For example, in the residential sector of China, the percentage of inverter ACs in total number of ACs has reached about 40% [11]. This percentage is even higher in developed countries such as Japan, the U.S. and some European countries [12]. Compared to single speed ACs, the compressor of an inverter AC is able to operate at variable speeds, and thus inverter ACs have some advantages including 1) higher comfort level because the indoor temperature is maintained within a narrow band around the set point, 2) lower power consumption when thermostatically operating around the set point [13], and 3) better performance during startup, grid voltage variation and locked-rotor periods [13].

In this context, some preliminary research has been conducted regarding the demand response from inverter ACs, which could be further classified into three categories. The first category of studies are to explore the load reduction from inverter ACs. Ninagawa et al established neural network models based on practical operational data of inverter ACs for simulating their load reduction response [14]. The practical communication environment was also emulated. Yang *et al.* [15] and Huang *et al.* [16] both focused on load reduction strategies of aggregated ACs. In [16], thermal comfort of customers was considered through a model embedded with predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD). In [15], the maximum duration of load reduction was considered. Considering the load reduction strategy proposed in [15], power system network planning problems were addressed in [17] and [18].

The second category of studies were made to control inverter ACs to arbitrage in electricity markets. Song et al modeled inverter ACs as a thermal battery to be compatible with power system dispatch models, and a hierarchical control framework was proposed to handle the heterogeneity of ACs, protect customers' privacy and reduce the computational burden [19]. Hu et al established models for inverter ACs and room thermal dynamics, and proposed temperature set point and frequency control methods for arbitraging in day-ahead and real-time electricity markets respectively [20], [21].

Furthermore, the third category of studies tried to control inverter ACs to provide ancillary services for power systems. Kim et al established a dynamic model of a variable speed heat pump (VSHP) responding to the frequency regulation signals, and small signal analysis was conducted to verify that direct load control could be generally applied to VSHPs [22]. Kim et al further conducted experimental studies to explore this research topic [23]. Hui et al proposed centralized and decentralized control methods for inverter ACs to provide primary frequency control services, with the signal delays and detection errors analyzed [24]. Viriyautsahakul et al proposed to control inverter ACs to provide reactive power support for power systems [25]. Yao et al proposed market based autonomous control for inverter ACs to provide ancillary services, such as frequency regulation and microgrid tie-line power smoothing [26]. The proposed control method is of good generalizability and protects the customers' privacy well. Customers' comfort is also able to be guaranteed fairly. Wang et al proposed a distributed consensus control method for controlling inverter ACs for renewable energy integration, where the impact of communication failure could be significantly reduced [27]. Cheng et al used inverter ACs to establish virtual synchronous generators to improve the inertia of power systems [28].

The work of this paper lies in the first category of studies as described above, focusing on the load reduction from the control of aggregated inverter ACs. However, compared to the existing studies, such as [14]–[18], this paper has the following contributions. Similar to that in [19], this paper models the space with inverter ACs as virtual energy storage systems (VESSs), but based on this model, this paper further proposes to control the ACs according to the descending order of virtual state of charge (VSOC) of VESSs. Moreover, an innovative 'temperature holding' strategy is proposed to conduct the load reduction for each inverter AC to guarantee that the indoor temperature will not deviate beyond the pre-agreed upper limit. Furthermore, this paper proposes a linear recovery strategy to reduce the load rebound after load reduction, which has not been considered in the existing studies regarding load reduction from inverter ACs. Besides, this paper pays special attention to the load reduction for the peak caused by the turning ON of large numbers of inverter ACs within a short period of time.

The paper is organized as follows. Section II presents the models involved in this work, including the electric model of an inverter AC, the thermodynamic model of the room, and the VESS model that encapsulates the room with an inverter AC. Section III presents the VSOC priority based load reduction control method with temperature holding and linear recovery strategies. Section IV presents the case studies. Finally, Section V concludes the paper.

II. MODELLING METHODOLOGY

In this section, the models involved in this paper are presented, including the electric model of an inverter AC, the thermodynamic model of the room, and the VESS model that encapsulates the room with an inverter AC.

A. THE ELECTRIC MODEL OF AN INVERTER AC

For a conventional single speed AC, hysteresis control with two thresholds is adopted to control the ON/OFF status of the compressor to maintain the indoor temperature within the thresholds. The compressor periodically turns ON/OFF when the indoor temperature hits the upper/lower temperature thresholds.

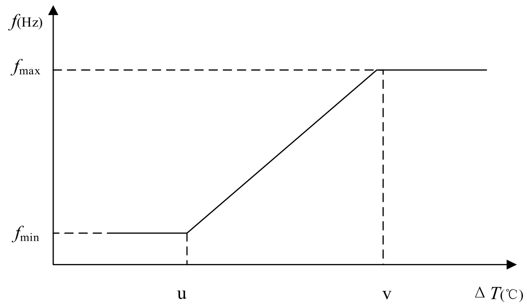

FIGURE 1. The relationship between the operating frequency and the difference between the indoor temperature and the set point for an inverter AC [29].

By contrast, for an inverter AC, the operating frequency of its compressor can be adjusted continuously, based on the difference between the indoor temperature and the temperature set point. Therefore, when the indoor temperature is far from the set point, the inverter AC will operate at high frequency to cool the space quickly. When the indoor temperature is close to the set point, the inverter AC will operate at low frequency to maintain the indoor temperature closely around the set point. In this way, inverter ACs can provide higher level of thermal comfort and consume lower level of electricity during the temperature maintaining stage compared with single speed ACs [13].

For an inverter AC which is turned ON, the relationship between the operating frequency and the difference between the indoor temperature and the set point is illustrated in Fig. 1 [29].

The relationship shown in Fig. 1 can be expressed as

$$f = \begin{cases} f_{\min} & \Delta T < u \\ \dfrac{f_{\max} - f_{\min}}{u - v} \cdot & \Delta T + \dfrac{(u-2v)f_{\max} - vf_{\min}}{u - v} \\ f_{\max} & \Delta T > v \end{cases} \quad (1)$$

where f(Hz) represents the operating frequency of the inverter AC; $f_{\min}$(Hz) and $f_{\max}$(Hz) are the minimum and maximum operating frequency of the inverter AC; ΔT(°C) is the difference between the indoor temperature and the set point; u(°C) and v(°C) are the knee points as illustrated in Fig. 1.

The cooling and electric power of the inverter AC can be simplified as linear functions of the operating frequency, which are expressed as [19]

$$Q = a \cdot f + b, \quad (2)$$
$$P = c \cdot f + d, \quad (3)$$

where Q(kW) and P(kW) represent the cooling and electric power of the inverter AC respectively. a(kW/Hz), b(kW), c(kW/Hz) and d(kW) are constant coefficients.

By taking (2) divided by (3), the coefficient of performance (COP) of the inverter AC is expressed as

$$COP = \frac{a \cdot f + b}{c \cdot f + d}. \quad (4)$$

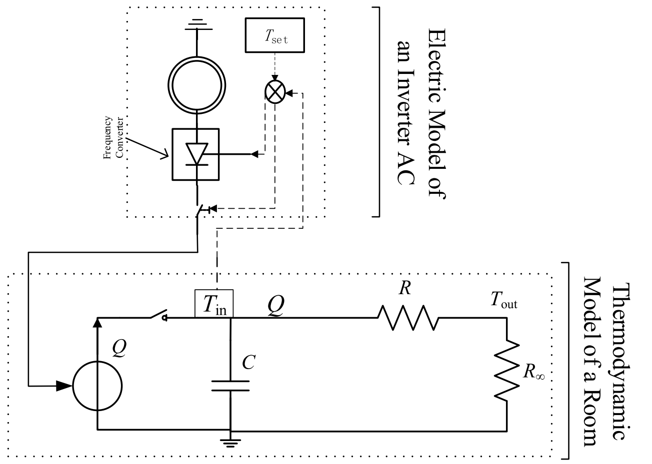

FIGURE 2. The model of the room with an inverter AC.

From (4), it is seen that the COP of an inverter AC is not a constant but varies with its operating frequency, which is different from that of a single speed AC.

B. THERMODYNAMIC MODEL OF A ROOM

The first order equivalent thermal parameters (ETP) model [7] is adopted in this paper to simulate the thermodynamics of the space installed with inverter ACs. The model is expressed as

$$C \cdot \frac{dT_{in}}{dt} = \frac{T_{out} - T_{in}}{R} - Q \quad (5)$$

where T_{in}(°C) and T_{out}(°C) represent the indoor and outdoor temperature; t is the variable representing the time; R(°C/kW) and C(kWh/°C) are the equivalent thermal resistance and thermal capacity respectively.

The differential equation (5) is discretized as the difference equation as follows:

$$T_{in}(t+1) = T_{out}(t) - QR - [T_{out}(t) - T_{in}(t) - QR] \cdot e^{-\Delta t/(RC)} \quad (6)$$

where Δt(h) is the length of a time step.

C. VESS MODEL ENCAPSULATING THE ROOM WITH AN INVERTER AC

Based on the electric model and thermodynamic model presented in the previous sub-sections (Sections II-A and II-B), the room with an inverter AC can be described by combining (1)-(6), which is illustrated in Fig. 2.

In order to conduct load reduction with minimum impact on customers' thermal comfort, which will be detailed in Section III, the rooms with inverter ACs are modeled as VESSs. First of all, analogous to the SOC of batteries, the VSOC of the VESS is defined as

$$VSOC = \frac{T_{in}^{\max} - T_{in}}{T_{in}^{\max} - T_{in}^{setpoint}} \quad (7)$$

where $T_{in}^{\max}$(°C) is the pre-agreed maximum indoor temperature during load reduction. Equation (7) is able to indicate the cooling energy stored in the room. When the indoor temperature T_{in} equals to the set point $T_{in}^{setpoint}$, the VSOC equals to 1 according (7), indicating that the room stores maximum level of cooling energy considering that normally the indoor temperature will not be lower than the set point. When the T_{in} equals to the maximum indoor temperature $T_{in}^{\max}$, the VSOC equals to 0, indicating that the cooling energy stored reaches the lowest allowed level. Therefore, normally the value of VSOC will range within [0, 1]. When T_{in} exceeds $T_{in}^{\max}$, the VSOC will be negative values, indicating that the VESS has been over-discharged, i.e. the customers' thermal comfort has been violated.

The charging/discharging of the VESS depends on relationship between the cooling power of the inverter AC and the stand-by heat gain of the room due to the higher outdoor temperature, as described in the right side of (5). When the cooling power is larger than the stand-by heat gain, the indoor temperature is decreasing according to (5), so that the VESS is charging to increase the VSOC according to (7). On the other hand, if the cooling power is lower than the stand-by heat gain, the indoor temperature is increasing according to (5), so that the VESS is discharging to decrease the VSOC according to (7).

III. CONTROL METHODOLOGY

In this section, a VSOC priority based control method with temperature holding and linear recover strategies is presented for control aggregated inverter ACs for load reduction.

A. LOAD REDUCTION SCHEME

In this paper, it is considered that power utilities contract with customers with inverter ACs to conduct load reduction during peak times of power systems, especially for those caused by simultaneous start-up of inverter ACs in summer. The magnitude and time duration of load reduction will be agreed in the contract. Moreover, the maximum indoor temperature during the load reduction will be agreed as well.

After the contracts are made, the power utility will directly control customers' inverter ACs in a centralized manner to conduct load reduction, based on some measurements taken from the customers. The specific control method used is presented in the following sub-sections.

B. TEMPERATURE HOLDING STRATEGY

The temperature holding strategy is to control each inverter AC selected for conducting load reduction. As presented in Section II-A, after an inverter AC is turned ON, the compressor of the AC will operate at variable frequencies to decrease the indoor temperature to the set point continuously. With the temperature holding strategy proposed in this paper, during the load reduction, the power utility will override the inherent control of the inverter AC, and instruct the inverter AC to operate at a fixed frequency which maintains the current indoor temperature unchanged.

This strategy is adopted because it is able to reduce the electric load of the AC without endangering customers' thermal comfort. From the angle of load reduction, the new fixed operating frequency instructed stops the indoor temperature from further decreasing, which thus results in less electric power consumption compared to that of the inherent control logic of the inverter AC. From the angle of customers' thermal comfort, the new fixed operating frequency is able to maintain the indoor temperature unchanged, so will not make the indoor temperature beyond the maximum limit agreed, as long as the indoor temperature is below the maximum limit before load reduction.

Specifically, the operating frequency of the AC to be controlled by the temperature holding strategy is calculated as follows. Firstly, as the indoor temperature is to be maintained unchanged, the target cooling power during load reduction should be

$$Q = \frac{T_{out} - T_{in}}{R}, \tag{8}$$

which is derived by setting dT_{in} as 0 in (5). Then the target operating frequency of the inverter AC during load reduction, f_{LR}(Hz), can be calculated by substituting (8) into (2), being

$$f_{LR} = \frac{T_{out} - T_{in} - R \cdot b}{R \cdot a}. \tag{9}$$

With the f_{LR} imposed on the inverter AC, the electric load reduction of this AC, ΔP(kW), can be calculated by

$$\Delta P = c \cdot (f_{original} - f_{LR}) + d. \tag{10}$$

where $f_{original}$ is the operating frequency of the inverter AC if no load reduction control is imposed, which can be calculated by (1).

C. VSOC PRIORITY BASED CONTROL

In order to meet the load reduction target, a subset of inverter ACs need to be selected to be controlled with the temperature holding strategy. The inverter ACs to be controlled are selected following the VSOC priority principle to minimize the impact of load reduction on customers' thermal comfort (which will be assessed and verified in Case 4 in Section IV). Specifically, the inverter ACs are selected to be controlled following the descending order of their VSOC until the load reduction target is satisfied. Note that if the VSOC is negative, the corresponding AC will not be controlled, because negative VSOC means that the indoor temperature has already exceeded the maximum limit (see Section II-C) and the temperature needs to be further decreased to satisfy customers' thermal comfort.

Mathematically, the VSOC priority based control can be expressed as

$$\begin{aligned} &\min_{\boldsymbol{J}^* \subseteq \boldsymbol{J}} \sum_{j \in \boldsymbol{J}^*} VSOC_j \\ &s.t.\ \ P_{baseline} - \sum_{j \in \boldsymbol{J}^*} P_j^{Ctrl} - \sum_{j \in \boldsymbol{J}-\boldsymbol{J}^*} P_j^{NonCtrl} \geq P_{reduction} \\ &\qquad VSOC_j \in (0, 1], \quad \forall j \in \boldsymbol{J}^* \end{aligned} \tag{11}$$

where $\boldsymbol{J}^*$ is the set of all the selected inverter ACs to be controlled; $\boldsymbol{J}$ is the set of all the ACs contracted with the power utility; j is the index of the AC; $P_{baseline}$(kW) is the baseline load of the population of the ACs for measuring the load reduction, and it equals to the aggregated electric power of the AC population just before the load reduction period starts; P_j^{Ctrl}(kW) and $P_j^{NonCtrl}$(kW) represent the electric power of the AC under control and not under control respectively; $P_{reduction}$(kW) is the load reduction target.

The objective function of (11) guarantees that the inverter ACs with highest VSOC are selected to be controlled. The first constraint in (11) ensures that the load reduction target is satisfied, while the second constraint ensures that only ACs with the indoor temperature below the maximum limit are controlled. Note that although (11) is formulated as an optimization problem, it is not solved through standard optimization solvers, but achieved through a serious of steps as summarized in the flow chart which will be presented later in Section III-E.

D. LINEAR RECOVERY STRATEGY

A sudden end of load reduction may result in severe load rebound, which may create a new peak for the power system. Therefore, a linear recovery strategy is proposed for tackling this issue. Specifically, within a pre-agreed length of recovery period after load reduction, the load reduction target is designed to diminish gradually, rather than to be set as 0 immediately. The load reduction target within the recovery period is expressed as

$$P_{reduction}^{recovery}(t) = \left(1 - \frac{t}{\tau_{recovery}}\right) \cdot P_{reduction} \; \forall t \in [0, \tau_{recovery}]. \tag{12}$$

where $P_{reduction}^{recovery}(t)$(kW) is the load reduction target at the time point t(h) in the recovery period, and $\tau_{recovery}$(h) is the length of the recovery period.

E. THE OVERALL FLOW CHART

The proposed VSOC priority based load reduction control method with temperature holding and linear recovery strategies is summarized as the flow chart shown in Fig. 3.

The flow chart is mainly composed of three parts: load reduction setting, load recovery setting and control of inverter ACs. Once the load reduction is needed, the load reduction target and period are set. Then the inverter ACs are controlled using the proposed temperature holding strategy in the descending order of VSOC. If the required amount of load reduction has been reached, or no more inverter ACs with eligible VSOC level can be controlled, the control in a time step finishes. This control procedure repeats for each time step until the load reduction period ends.

After the load reduction ends, the load recovery process starts, where the load reduction target diminishes gradually until the end of the recovery period. Finally, the whole load reduction and recovery process ends.

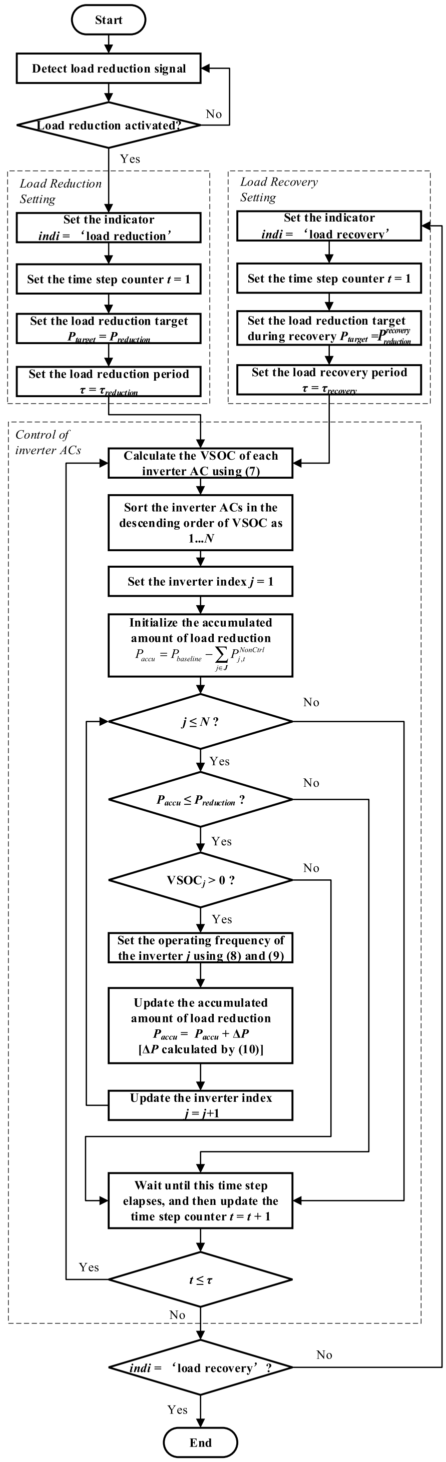

FIGURE 3. The overall flow chart of the proposed load reduction method.

IV. CASE STUDIES

In this section, several case studies are presented to verify the effectiveness of the proposed load reduction control method for inverter ACs.

A. CASE DESIGN

The load reduction of a population of 100 inverter ACs was simulated and studied. The required amount of load reduction

TABLE 1. Parameters of the inverter ACs and rooms.

Parameters	Values
a (kW/Hz)	$25+\hat{a}$, where $\hat{a}\sim N(0,2)$
b (kW)	$200+\hat{b}$, where $\hat{b}\sim N(0,20)$
c (kW/Hz)	$14+\hat{c}$, where $\hat{c}\sim N(0,1)$
d (kW)	$-75-\hat{d}$, where $\hat{d}\sim N(0,25)$
u (°C)	-1
v (°C)	3
$f_{\max}$ (Hz)	$\sim U(140,150)$
$f_{\min}$ (Hz)	$\sim U(20,30)$
$T_{in}^{setpoint}$ (°C)	$\sim U(24,25)$
$T_{in}^{\max}$ (°C)	$\sim U(26,27)$
R (°C/kW)	$\sim U(5.4,5.6)$
C (kWh/°C)	$\sim U(0.17,0.19)$

* $N(\mu,\sigma)$ represents a normal distribution with the mean being μ and the standard deviation being σ; $U(m,n)$ represents a uniform distribution with the values lying between m and n.

was assumed to be 30 kW, and the load reduction period was assumed to be 1 hour, starting from the 20th minute and ending at the 80th minute. Before the load reduction period, the 100 inverter ACs were assumed to be turned ON in batches within a short period of time (within 20 minutes), which created a peak and triggered the load reduction. After the load reduction period, a recovery period of 40 minutes was considered. The parameter settings of the inverter ACs and the associated rooms are listed in Table 1.

With the above setting, totally 4 cases were studied, which are summarized as follows:

- Case 1: a case which shows the evolvement of electric power consumption and indoor temperature of the inverter ACs without enforcing any load reduction, to test the AC and room models used in this paper and act as a reference case.
- Case 2: a case with the proposed load reduction method enforced, to verify its effectiveness.
- Case 3: a case with the proposed load reduction method enforced without executing any recovery strategy, to verify the validity of the proposed linear recovery strategy.
- Case 4: a case where the proposed load reduction method was enforced with the ACs controlled in a random order instead of the descending order of VSOC, to verify the benefits of the VSOC priority based approach proposed. The sensitivity of the magnitude of the load reduction target was also examined in this case.

B. CASE 1: REFERENCE CASE

In this case, the inverter ACs were turned ON in batches within 20 minutes but no load reduction was enforced. The simulation results are shown in Figs. 4-7.

In Fig. 4, it is seen that the aggregated electric power of the AC population quickly increased to a peak over 130 kW, with the turning ON of the ACs in batches within 20 minutes. After reaching the peak, the aggregated electric power gradually decreased to a stable level of about 80 kW, with the indoor temperature of the associated rooms gradually reduced towards the set points as shown in Fig. 5. It is calculated that the peak load of the AC population is about 62.5% higher than the stable load, which highlights the importance of conducting load reduction.

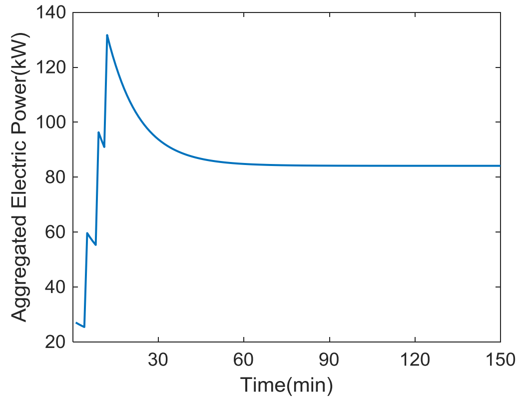

FIGURE 4. The aggregated electric power of the inverter AC population without load reduction (Case 1).

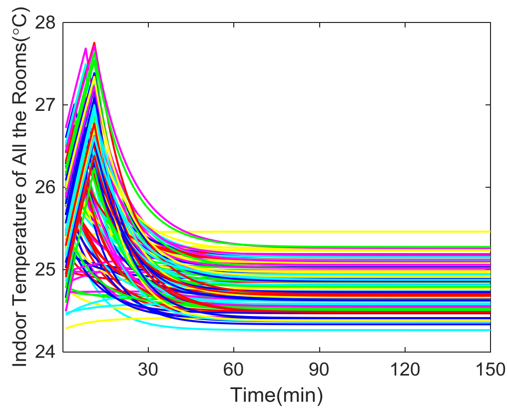

FIGURE 5. The indoor temperature of the rooms without load reduction (Case 1).

Figs. 6 and 7 show the electric power and indoor temperature of a selected inverter AC and the associated room. From Fig. 6, it is seen that the inverter AC was turned ON at the first minute of the simulation, with a high initial electric power consumption close to 1.5 kW. Then the electric power decreased gradually to a stable level of about 0.85 kW. Observing Fig. 7, it is seen that the change of the indoor temperature has the similar trend as that of the electric power shown in Fig.6, verifying that the electric power of an inverter AC is proportional to the difference between the indoor temperature and the set point, as presented in Section II-A.

In Fig. 7, it is also worth noting that the final stable indoor temperature is slightly larger than the set point. In some other studies, the final stable indoor temperature will fluctuate around the set point, such as that in [12], [15] and [26].

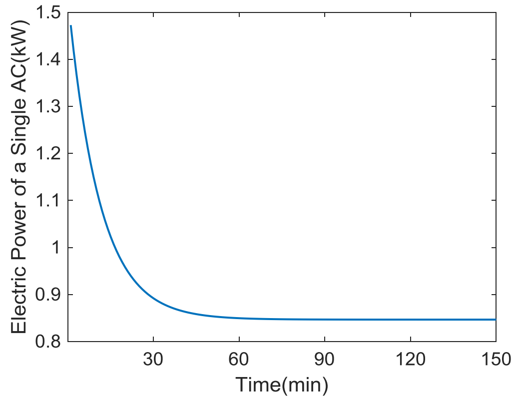

FIGURE 6. The electric power of one inverter AC without load reduction (Case 1).

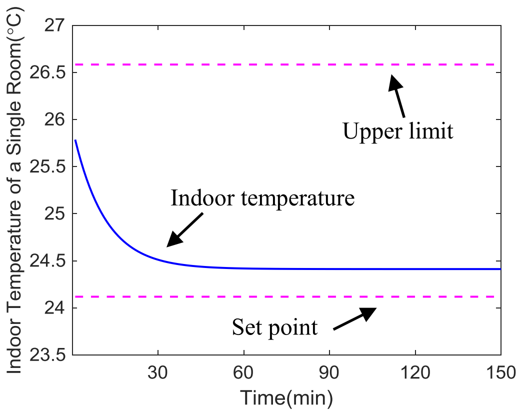

FIGURE 7. The indoor temperature of one room without load reduction (Case 1).

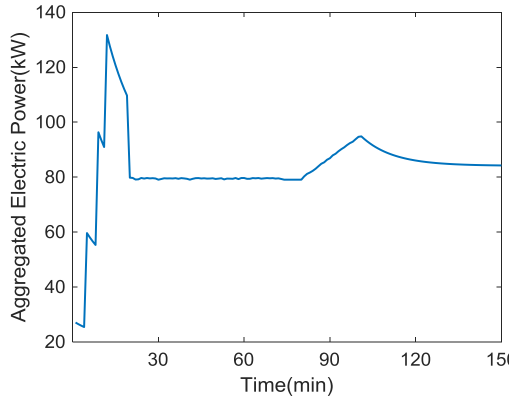

FIGURE 8. The aggregated electric power of the inverter AC population with load reduction (Case 2).

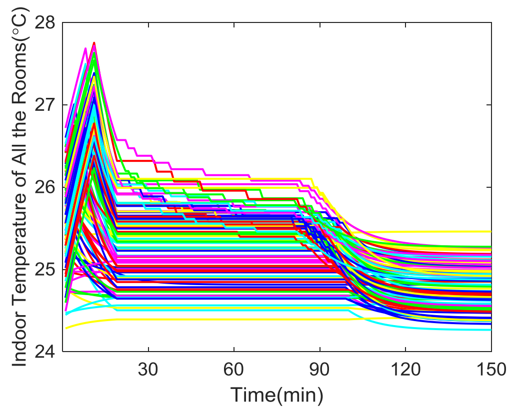

FIGURE 9. The indoor temperature of the rooms with load reduction (Case 2).

This is because a linear function, as used in [19], is used to describe the relationship between the operating frequency and electric power of the inverter AC in this paper [see (3) in Section II-A], but in [12], [15] and [26], a more accurate non-linear function is used. Although a more simplified function is used in this paper, it is sufficient to demonstrate and verify the performance of the load reduction method proposed. After all, the focus of this paper is not the detailed modeling of inverter ACs.

C. CASE 2: LOAD REDUCTION CASE

In this case, the load reduction described in the case design (see Section IV-A) was enforced for the AC population. The results are shown in Figs. 8-11.

Fig. 8 shows that the load reduction was activated soon after the peak load was detected, and lasted for 1 hour till the 80th minute. It is seen that the aggregated power of the AC population was controlled around 80 kW during the load reduction, reducing 30 kW load compared to the time point when the load reduction was activated. After the load reduction period ended, there was a mild load rebound for about 40 minutes. Then the aggregated power gradually converged to a stable value. Fig. 8 verified that the proposed load reduction method is able to achieve the intended target.

Figs. 10 and 11 show the electric power and indoor temperature of a selected inverter AC and the associated room. From Fig. 11, it is seen that the indoor temperature kept unchanged during the load reduction. This verified that during the load reduction, the operating frequency of the inverter AC was reduced to a value which stopped the indoor temperature from further decreasing, as described in the temperature holding strategy (see Section III-B). As a result, the electric power of the inverter AC was reduced accordingly during the load reduction, as shown in Fig. 10.

From Fig. 9 where the indoor temperature of all the inverter ACs is illustrated, it is seen that the indoor temperature of some rooms still decreased in a staircase-like way during the load reduction period. This is because the load reduction was conducted following a VSOC priority principle. For some ACs, at the beginning they might be controlled for load reduction, but after some time, some other ACs which had higher VSOC might take their place so that they were no longer controlled and re-started to cool the rooms normally.

D. CASE 3: ASSESSMENT OF THE LOAD RECOVERY STRATEGY

In this case, the load reduction without any recovery strategy enforced was conducted to demonstrate the effectiveness of

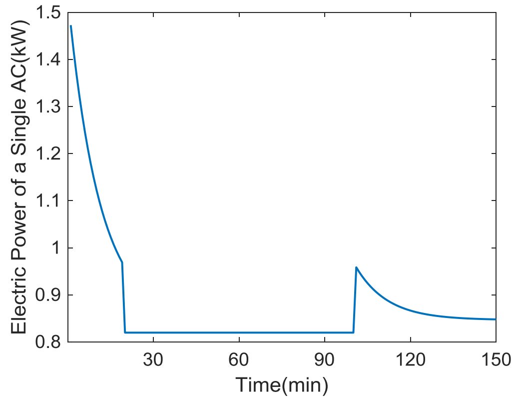

FIGURE 10. The electric power of one inverter AC with load reduction (Case 2).

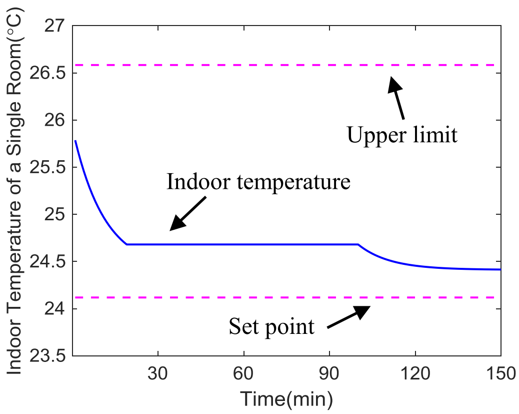

FIGURE 11. The indoor temperature of one room with load reduction (Case 2).

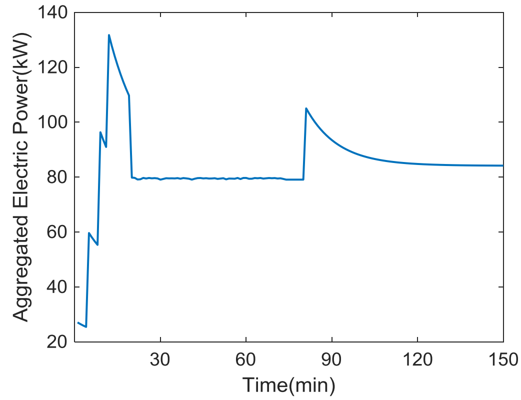

FIGURE 12. The aggregated electric power of the inverter AC population with load reduction but without any recovery strategy (Case 3).

TABLE 2. Comparison of the proposed load reduction method with the reference method with random selection.

Load Reduction Target (kW)	Proposed VSOC Priority based Method		Reference Method with Random Selection	
	Reduction Error	Temperature Deviation (°C)	Reduction Error	Temperature Deviation (°C)
20	0.0 %	0.54	0.0 %	0.63
25	0.0 %	0.66	0.0 %	0.78
30	0.0 %	0.88	0.0 %	1.00
35	11.0 %	0.94	10.7 %	1.04
40	22.1 %	0.96	21.8 %	1.04
50	37.7 %	0.98	37.5 %	1.04
60	48.1 %	0.99	47.9 %	1.04

the proposed linear recovery strategy. The results are shown in Fig. 12.

Comparing Fig. 12 with Fig. 8, it is seen that without any recovery strategy, there would be a much steeper load rebound than that with the linear recovery strategy. Without any recovery strategy, the maximum magnitude of load rebound was 105 kW, which was 21% higher than that with the proposed linear recovery strategy enforced (being 95 kW). This verified that the proposed linear recovery strategy is able to effectively reduce the negative impact of load rebound after load reduction.

E. CASE 4: ASSESSMENT OF THE VSOC PRIORITY BASED CONTROL

This case compares the performance of the proposed VSOC priority based control with a reference control of which the inverter ACs to be controlled are decided by random selection rather than by the descending order of VSOC. The other settings of the reference method, such as the temperature holding and linear recovery strategies, are all the same as those of the proposed load reduction method. The comparison results are presented in Table 2.

In Table 2, the load reduction methods, both the proposed and reference ones, are evaluated by two indexes, 'Reduction Error' and 'Temperature Deviation'. The Reduction Error is defined as the average relative error between the actual load reduction and the targeted load reduction throughout the whole load reduction period, which quantifies the performance of a control method in terms of load reduction. The mathematical expression is as follows:

$$\text{Reduction Error} = \frac{\sum_{t\in\boldsymbol{T}}\left|P_{baseline} - \sum_{j\in\boldsymbol{J}^*} P_{j,t}^{Ctrl} - \sum_{j\in\boldsymbol{J}-\boldsymbol{J}^*} P_{j,t}^{NonCtrl}\right|}{|\boldsymbol{T}|\cdot P_{reduction}} \tag{13}$$

where $\boldsymbol{T}$ represents the set of all the time steps across the load reduction period, and the meanings of other symbols have been explained below (11). In (13), the numerator represents the actual load reduction while the denominator represents the targeted load reduction.

The Temperature Deviation is defined as the standard deviation of the indoor temperature from the set points among all the rooms, which quantifies the average thermal comfort level of all the customers involved during the load reduction. The mathematical expression is as follows:

$$Temperature\ Deviation = \sqrt{\frac{\sum_{t\in \boldsymbol{T}}\sum_{j\in \boldsymbol{J}}\left(T_{in,j,t} - T_{in,j}^{setpoint}\right)^2}{|\boldsymbol{T}|\cdot|\boldsymbol{J}|}}. \tag{14}$$

The larger the temperature deviation is, the worse the overall thermal comfort level of the population will be.

From Table 2, it is seen that for both control methods, the reduction errors for the load reduction targets below 30 kW are all zero, but increase gradually with the targets over 30 kW. This shows that the load reduction capability of the AC population has an upper limit, being around 30 kW in this case, which is decided by the summation of the capability of each inverter AC of which the VSOC is between 0 and 1.

Comparing the Temperature Deviations of the proposed and reference methods in Table 2, it is seen that the values of the proposed method are lower than those of the reference method, especially when the load reduction targets are within the AC population's capability (i.e. when the load reduction targets are below or equal to 30 kW). This is because the proposed VSOC priority based control will always control the ACs of which the indoor temperature are closer to the set points, giving those with higher indoor temperature the opportunities to pull the indoor temperature back to the set points. By contrast, the reference method just randomly selects the ACs to be controlled, making the indoor temperature of some rooms far from the set points. As a result, the proposed VSOC priority based control is able to better take care of customers' thermal comfort, as justified by the values of Temperature Deviations in Table 2.

Comparing the proposed method with the reference method, it is seen from Table 2 that, when the load reduction target was no higher than 30 kW, the proposed method could result in lower temperature deviations (and thus less compromise of customers' thermal comfort) than those of the reference method, with the same reduction errors (all being zero). Therefore, in these scenarios, the proposed method was always preferable to the reference method. When the load reduction target was higher than 30 kW, the proposed method still resulted in lower temperature deviations than those of the reference method, but at the cost of higher reduction errors. However, in these scenarios, the temperature deviations of the proposed method were significantly lower than those of the reference method (being 9.6%, 7.7%, 5.8% and 4.8% lower at the load reduction target of 35 kW, 40 kW, 50 kW and 60 kW, respectively), whereas the reduction errors of the proposed method were just slightly higher than those of the reference method (being 2.8%, 1.4%, 0.5% and 0.4% higher at the load reduction target of 35 kW, 40 kW, 50 kW and 60 kW, respectively).

In practice, the value of load reduction services for the power utility depends on the cost needed to purchase alternative services if not using load reduction services (e.g. from conventional generators). The cost of temperature deviation for the power utility is that, if the temperature deviation is higher, the power utility may have to pay more remuneration to customers for recruiting them to join the load reduction scheme. Therefore, for the results shown in Table 2, when the load reduction target was higher than 30 kW, detailed economic calculation would need to be conducted to decide to use the proposed method (with lower temperature deviation but higher reduction error) or the reference method (with higher temperature deviation but lower reduction error), or even not to conduct any load reduction. When the load reduction target was no higher than 30 kW, although the proposed method was always preferable to the reference method, economic calculation would also need to be conducted to weigh the benefits and costs of conducting load reduction, and then to decide whether and how much load reduction should be conducted. Detailed economic assessment depends on the features of specific electricity markets, power systems and customers, and is somehow out of the scope of this paper. However, it is a valuable research topic for the future.

V. CONCLUSION

A virtual state of charge priority based control method with temperature holding and linear recovery strategies was proposed in this paper for conducting load reduction of aggregated inverter air conditioners. A virtual energy storage system model that encapsulates the room with an inverter AC was established, based on the electric model of an inverter AC and the thermodynamic model of a room, for designing, simulating and assessing the load reduction control method proposed.

Simulation results verified the models established and the load reduction control method proposed. It was verified that the proposed control method was able to realize the targeted load reduction without violating the maximum indoor temperature limits. It was also verified that the proposed linear recovery strategy was able to effectively reduce the load rebound after the load reduction. The load rebound was reduced by 21% in the case study. Finally, compared with a reference method that randomly selected ACs for being controlled, the proposed VSOC priority based control was able to reduce the deviation of indoor temperature from the set points for the whole AC population, thus resulting in higher thermal comfort for customers.

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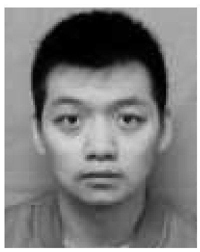

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